Evaluation of the Moderate Resolution Imaging Spectrometer special 3.95-μm fire channel and implications on fire channel selections for future satellite instruments

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Abstract. The 3.75-μm and 11-μm channels on the polar orbiting NOAA Advanced Very High Resolution Radiometer (AVHRR) sensors have saturation temperatures of approximately 325 K. They allowed limited successes in estimating the sub-pixel fire temperature and fractional area coverage. The saturation problem associated with the 3.75-μm AVHRR channel greatly limited the ability for such estimates. In order to overcome this problem, the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the NASA Terra and Aqua spacecrafts have both been equipped with a special fire channel centered at 3.95 μm with a specified saturation temperature of 500 K and a spatial resolution of 1 km. We have analyzed more than 40 sets of Terra and Aqua MODIS fire data acquired over different geographical regions, and found that very few fire pixels have the 3.95-μm fire channel brightness temperatures greater than 450 K. We suggest that the saturation temperature of fire channels near 4 μm for future satellite instruments with pixel sizes of about 1 km should be specified at about 450 K or even slightly lower in order to make the channels more useful for quantitative remote sensing of fires. A dual gain approach should also be considered for future satellite fire channels.

Keywords: MODIS, satellite instrument, fire channel.

1 INTRODUCTION

Biomass burning is a major source of trace gases and aerosol particles, with significant ramifications for atmospheric chemistry, cloud optical and micro-physical properties, and radiation budgets [1]. Remote sensing of fires and hot surfaces on regional and global scales can be made from satellite platforms. For examples, the polar orbiting NOAA Advanced Very High Resolution Radiometer (AVHRR) sensors and the visible atmospheric sounder (VAS) sensors on the Geostationary Orbiting Environmental Satellite (GOES) platforms have been used for remote sensing of fires [2], [3]. Dozier [4] first introduced a theoretical technique to study sub-pixel temperature fields using the 3.75- and 11-μm AVHRR channels. He approximated the temperature field of each pixel by two areas of uniform temperature: the background area and a target area, which occupies a fraction of the pixel. Dozier demonstrated that a sub-resolution high temperature target is detectable because it has a greater sensitivity in the 3.75-μm channel than in the 11-μm channel. Matson and Dozier [5] applied this fire detecting approach to AVHRR data on fixed targets with known locations – a high temperature industrial source in Detroit and waste gas flares in the Persian Gulf. Matson

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et al. [2] used AVHRR images over the United States and Brazil for fire detections based on enhanced brightness temperatures (BTs) in the 3.75-μm channel. Numerous other researchers [6], [7], [8], [9], [10], [11], [12]. [13] have reported fire detections using BT differences between channels near 4 μm and 11 μm as one of the detecting criteria.

The 3.75-μm and 11-μm AVHRR channels were originally designed mainly for remote sensing of clouds and sea surface temperatures (SST). The two channels have saturation temperatures of approximately 325 K. Although they allowed limited successes in estimating the sub-pixel fire temperature and fractional area coverage, the saturation problem associated with the 3.75-μm AVHRR channel over hot surfaces greatly limited the ability for such estimates [5]. In order to overcome this problem, the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments [14], [15] on the NASA Terra and Aqua spacecrafts have both been equipped with a special fire channel centered near 3.95 μm with a specified saturation temperature of 500 K. The channel has a spatial resolution of 1 km at nadir. It was hoped that the increased saturation level would permit better estimates of sub-pixel fire temperature and fractional area coverage from MODIS data. Although more than seven years of Terra MODIS data are now publicly available, we are unaware of any reported studies in the literature on simultaneous retrievals of sub-pixel fire temperatures and area fractions from MODIS data. The noise and calibration uncertainty of the special 3.95-μm fire channel make it difficult to perform the studies.

We have analyzed Terra and Aqua MODIS fire data sets acquired over different geographical regions, and systematically studied 3.95-μm BT distributions for fire pixels. In this paper, we report our observations from the MODIS data sets. We also present recommendations on selection of saturation temperatures of fire channels near 4 μm for future satellite instruments.

Table 1. Main characteristics of three MODIS channels and two AVHRR channels commonly used for fire detections.

Channel	Center Wavelength (μm)	Maximum T (K)
MODIS Ch. 21	3.959	500
MODIS Ch. 22	3.959	328
MODIS Ch. 31	11.03	400 (Terra MODIS) 340 (Aqua MODIS)
AVHRR Ch. 3	~3.75	~325
AVHRR Ch. 4	~10.8	~325

2 INSTRUMENT CHARACTERISTICS

At present, there are two MODIS instruments in space – one on the NASA Terra spacecraft and the other on the Aqua spacecraft. Both instruments have 36 spectral channels between 0.4 and 14.4 μm for remote sensing of land, ocean, and atmosphere. Table 1 lists the main characteristics of three MODIS channels and two AVHRR channels commonly used for remote sensing of fires. The two MODIS instruments are equipped with a special 3.95-μm channel, Channel 21, with a high saturation temperature of 500 K for remote sensing of fire. Both instruments have another channel, Channel 22, centered at the same wavelength of 3.95 μm with a saturation temperature of 328 K. Channel 21 has a digitization noise of 0.8 K for a pixel at 300 K. Channel 22 has a much smaller digitization noise of 0.03 K for the same pixel. Because Channel 22 is less noisy and has a much smaller digitization noise than Channel 21, the MODIS operational fire algorithm [13] makes use of Channel 22 whenever it is possible. When Channel 22 is saturated, it is replaced with the high saturation Channel 21 for fire detections.

The Terra MODIS instrument has an additional 11-μm channel, Channel 31, with a saturation temperature of 400 K for remote sensing of fire, land and sea surface temperatures. The saturation temperature for the 11-μm channel on the Aqua MODIS instrument was lowered to 340 K in order for the channel to be more suitable, with improved sensitivity or reduced digitization noise, for remote sensing of SSTs [16], [17].

During the early definition phase of MODIS instrument in 1991, the special 3.95-μm fire channel was selected to center at 3.75 μm, similar to the AVHRR Channel 3, but with a saturation temperature of 700 K, which was listed in Table 1 of King et al. [15]. The 3.75-μm AVHRR channel is known to be affected by atmospheric water vapor absorption [4]. At 3.95 μm, the water vapor absorption effect is far less than that at 3.75 μm. At the time, it was also known that, although active fires have temperatures on the order of 1000 K, they occupy only small area fractions (< 10%) of the 1 km pixels. In view of these factors, Bo-Cai Gao and Yoram J. Kaufman suggested to the MODIS Project Office in the fall of 1992 that the center wavelength of the MODIS special fire channel should be shifted to 3.95 μm, and the saturation temperature should be decreased to about 500 K. The two suggestions were adopted by the MODIS Project in December of 1992. Subsequently, the specification for the MODIS special fire channel was modified.

3 DATA ANALYSIS AND RESULTS

The high saturation temperature of 500 K for the MODIS special fire channel (Ch. 21) centered near 3.95 μm often makes the images of this channel noisy and less accurate. The 10% specified calibration accuracy corresponds to a 3 K difference when the scene temperature is about 330 K. The noise and calibration uncertainty for the special fire channel make it difficult to use the Dozier technique [4] for the simultaneous estimates of fire temperatures and fire area fractions, as originally intended. They have also limited the usage of the special fire channel in the operational MODIS fire algorithm [13]. In view of these situations, we have decided to make an analysis of Terra and Aqua MODIS fire data sets and to see if the saturation temperature for the special 3.95-μm fire channel was specified too high. Specifically, we have studied BT distributions of more than 40 sets of MODIS imaging data acquired over different geographical regions.

An example of fire imaging scene is shown in Figure 1. We randomly selected this scene from many fire scenes posted on the web site of MODIS Rapid Response Team (http://rapidfire.sci.gsfc.nasa.gov/). The Fig. 1 true color image (Red: 0.66 μm, Green: 0.55 μm; Blue: 0.47 μm) was acquired with the Aqua MODIS instrument over South America on September 14, 2004. The image is centered near a latitude of 14°S and a longitude of 64°W. The high elevation Andes Mountain areas in the lower left portion of the scene are quite clear. The areas east and north to the mountains are covered by heavy smoke. We use the two "absolute" fire detection criteria of Justice et al. [13] to identify active fires and hot surface areas. The areas with BT of 360 K or greater for the special 3.95-μm fire channel are flagged as "red" pixels. The areas with the special 3.95-μm fire channel BTs greater than 330 K and with BT differences between the special fire channel and the 11-μm channel greater than 25 K are also flagged as "red" pixels. The individual fire pixels are difficult to see in the resulting image. In order to allow the fire pixels to be seen, we have expanded the "red" areas around the detected fire pixels in Fig. 1.

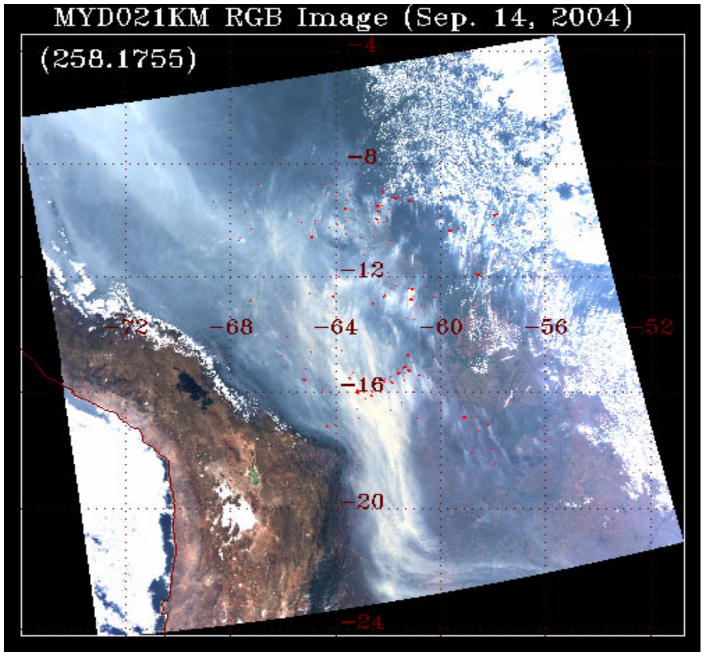


Fig. 1. A true color Aqua MODIS image (red: 0.66 µm; green: 0.55 µm; blue: 0.47 µm) acquired over South America on September 14, 2004. Large areas are covered by smoke. Fire pixels are marked in red color. See text for detailed descriptions.

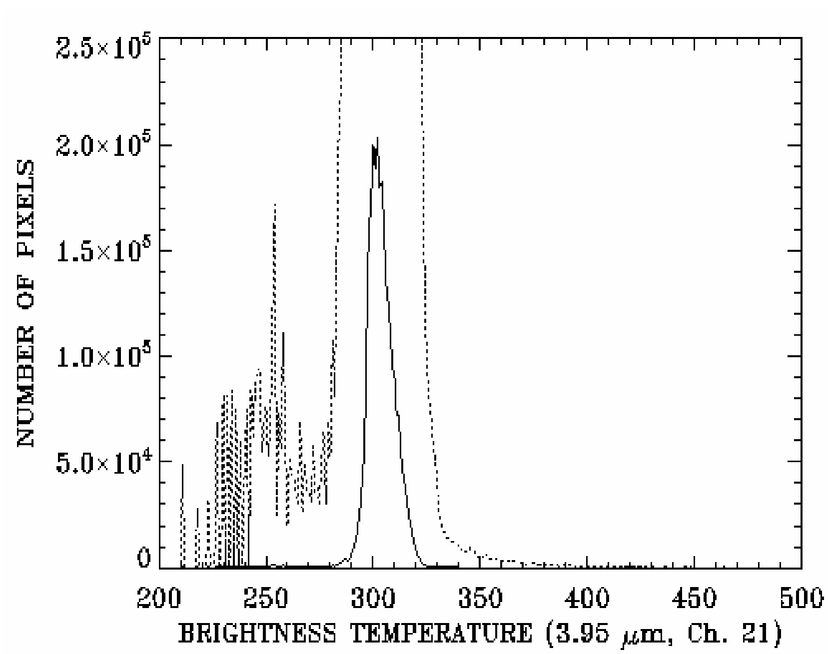


Fig. 2. The histogram (solid line) of brightness temperatures of the MODIS special 3.95-µm fire channel for the Fig. 1 scene, and the histogram multiplied by 100 (dotted line) for better viewing of the tails in the left and right portions of the histogram.

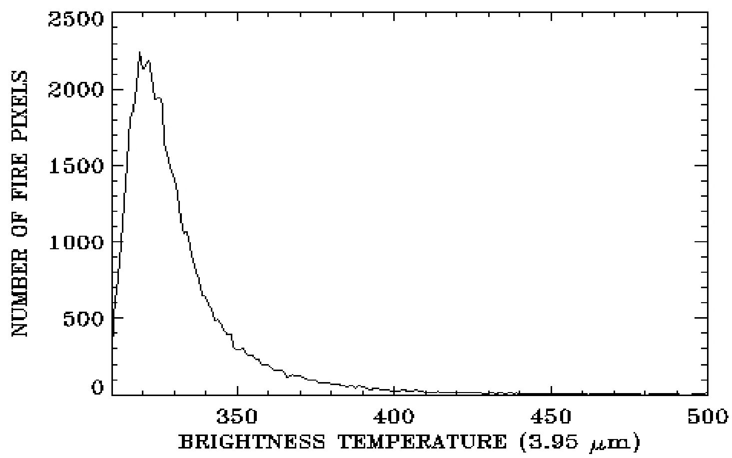
The solid line in Figure 2 shows the BT histogram of the special 3.95-μm fire channel for the whole scene. The center portion of the curve follows closely to a Gaussian distribution. Most of the pixels are located in the BT range between 280 K and 330 K. There are not many pixels with BTs less than 280 K or greater than 330 K. In order to allow the left and right tails of the histogram to be seen better, we scaled the histogram by a factor of 100. The scaled histogram is shown as the dotted line in Fig. 2. The left portion of the scaled histogram (< 280 K) is quite bumpy due to noise. The right portion of the histogram (> 330 K) shows that the number of pixels with BT greater than 400 K are quite small, and almost no pixels have BTs greater than 450 K. This indicates that active fires occurred during a fire season in South American do not reach the 500 K saturation temperature for the MODIS special 3.95-μm fire channel.

In order to make a more comprehensive study of fire temperatures, we have ordered more than 40 sets of Terra and Aqua MODIS fire data products from the NASA Eros data center. The data products were generated with the so called "Collection 4" MODIS fire algorithm [18]. Table 2 is a list of the fire data sets used in this study. Figure 3a shows the histogram of 3.95-μm BT distributions of fire pixels from all the data sets. Most of the fire pixels have BTs less than 400 K, and very few pixels have BTs greater than 450 K. Figure 3b shows the normalized cumulative histogram of BTs for all the fire pixels. The digital data of the normalized cumulative histogram demonstrates that 90% of the fire pixels have BTs less than 354 K, 95% less than 371 K, and 99.6% less than 450 K.

Table 2. A list of 44 MODIS fire data sets used in this study.

Location	Date	Time (UTC)	Location	Date	Time (UTC)
North America	08/21/2000	18:55	North America	08/22/2000	18:00
North America	08/23/2000	18:45	North America	08/25/2000	18:30
North America	08/26/2000	19:15	Australia	12/25/2001	23:45
Australia	12/29/2001	00:15	Australia	12/31/2001	00:00
Australia	01/01/2002	23:50	Australia	01/08/2002	23:55
Africa	04/02/2002	08:35	Africa	04/07/2002	08:55
Africa	04/16/2002	08:40	Africa	05/07/2002	09:05
Africa	05/09/2002	08:50	Africa	05/11/2002	08:40
Africa	05/14/2002	09:10	Africa	05/20/2002	08:35
North America	06/21/2002	18:15	North America	07/02/2002	16:15
North America	07/06/2002	15:50	Australia	02/04/2003	00:00
Australia	02/07/2003	00:30	Central America	05/05/2003	16:50
South America	09/06/2004	14:20	Australia	02/04/2003	04:10
South America	08/01/2003	17:15	South America	08/13/2004	17:40
Africa	08/05/2004	12:10	South America	09/14/2004	17:55
South America	09/18/2004	17:30	India	10/25/2004	08:10
Africa	01/03/2005	12:20	Europe	08/04/2003	11:30
Europe	08/04/2005	11:10	Europe	08/04/2003	13:05
Europe	08/02/2004	13:30	Europe	08/05/2005	13:30
Europe	08/03/2003	14:00	Siberia (Russia)	07/25/2003	00:50
Siberia (Russia)	07/26/2003	03:30	Siberia (Russia)	07/26/2003	03:35
Siberia (Russia)	07/26/2003	01:45	Siberia (Russia)	08/04/2003	01:40

(A)



(B)

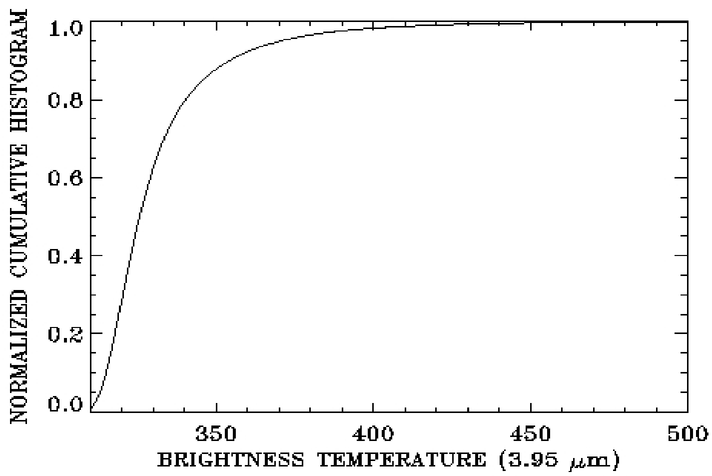


Fig. 3. (A) – The histogram of 3.95-µm brightness temperature distributions of fire pixels in the 44 MODIS scenes listed in Table 2, and (B) the normalized cumulative histogram.

4 IMPLICATIONS ON FUTURE SATELLITE SENSORS

The histograms in Fig. 2 and Fig. 3a and the normalized cumulative histogram in Fig. 3b have demonstrated that less than 0.5% of fire pixels have BTs greater than 450 K. If the MODIS special 3.95-µm fire channel's saturation temperature were set at 450 K, the resulting channel's ability in detecting very hot fires would be hardly affected. The detector quantization step would be about 44% of that for the 500 K saturation temperature, based on calculations of Plank function for different temperatures. The refined digitization step would have allowed improved remote sensing of fires. If the MODIS special 3.95-µm fire channel's saturation temperature were set at 400 K, approximately 1.7% of the fire pixels would have been saturated (see Fig. 3b), but the digitization step would be reduced to roughly 16% of that for the 500 K saturation temperature. The further refined digitization step would have greatly benefited the remote sensing of most fires (~98.3%).

Based on the above analysis, we suggest that future satellite designers should understand the limitations with the MODIS special fire channel. The saturation temperature for a channel near 4 μm with a pixel size of about 1 km on the ground should be lowered to about 450 K, or even further lowered to 400 K, if the channel uses the single gain setting approach. An alternative fire channel design is to use a dual gain approach. This approach will substantially reduce the digitization noise when the scene temperature is low with the high gain setting. When the scene temperature is high, the channel will automatically switch to the low gain setting.

The developers of the MODIS Active Fires algorithm decided not to generate operational fire temperature and fractional area coverage data products in late 1992 because of large noise and radiometric calibration uncertainties associated with the special fire channel at the high saturation temperature of 500 K. They decided to produce the fire mask and the fire thermal energy as parts of the standard MODIS fire data products. If the saturation temperature for a future satellite fire channel near 4 μm with a ground pixel size of about 1 km is lowered to 450 K, or even further to 400 K, the noise of the channel and radiometric calibration uncertainties will be significantly reduced. The fire algorithm developers should consider generating operational fire temperature and fractional area coverage data products using algorithms similar to the one developed by Dozier [4].

5 SUMMARY

Through analysis of MODIS fire data sets acquired over different geographical locations, we have found that very few fire pixels have brightness temperatures greater than 450 K for the special fire channel near 4 μm. We feel that the saturation temperature of the fire channel, although decreased from the initial 700 K to 500 K, should have been decreased further. It is recommended that the saturation temperature of fire channels near 4 μm for future satellite instruments with pixel sizes of about 1 km on the ground should be specified at about 450 K or even lower to 400 K in order to make the channels more useful for quantitative remote sensing of fires.

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